Composites Part B 77 (2015) 10–18

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Energy absorption and load carrying capability of woven natural silk epoxy–triggered composite tubes

R.A. Eshkoor*, A.U. Ude, A.B. Sulong, R. Zulkifli, A.K. Ariffin, C.H. Azhari

Department of Mechanical and Materials Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia, UKM, 43600 Bangi, Malaysia

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form
26 January 2015
Accepted 3 March 2015
Available online 11 March 2015

Keywords:
A. Fabrics/textiles
C. Damage mechanics
D. Mechanical testing
E. Lay-up (manual/automated)
Natural silk composite

ABSTRACT

This study investigated the energy absorption response and load carrying capability of woven natural silk/epoxy–triggered composite rectangular tubes subjected to an axial quasi-static crushing test. The rectangular composite tubes were prepared by hand lay-up technique. The tubes consisted of 12, 24, and 30 layers of natural woven silk/epoxy laminate and were 50, 80, and 120 mm long. The crashworthiness of the tubes was evaluated by measuring the specific energy absorption in quasi-static axial compression. Specific energy absorption was obtained from the load–displacement curve during testing. The failure mode of the tubes was analyzed from high resolution photographs obtained. Overall, the tube with 50 mm length and 30 layers showed the best crashworthiness among the tubes. The failure morphology showed that the specimens failed in two distinct modes: local and mid-length buckling. The triggered composite tubes exhibited progressive failure.

1. Introduction

Composites have long been used as materials in different structures because of their highly specific stiffness and strength. Global warming due to carbon emissions from factories has been a significant environmental concern in recent years. Therefore, composites that are environmental friendly are highly desirable [1]. Natural fibers have lower density than synthetic fibers and have high tensile strength and stiffness; in addition, they are annually renewable and are biodegradable [2]. In addition, the specific mechanical properties of many natural fiber composites are comparable with those of glass fiber counterparts [3,4].

Natural fibers (NF) can be derived from minerals, plants, or animals [5]. Plant-based fibers include bast, leaf, seed, wood, grass, and straw. Animal-based fibers include hair, wool, and silk. Mineral fibers, such as asbestos, are not considered for use in NF-composites because they are non-renewable and sometimes carcinogenic [2]. The use of animal-based natural fibers, such as silk and wool, has been rarely reported in bio-based-composites [6]. Natural silk has been employed in the textile industry since ancient times [7]. Silk fibers are biodegradable and highly crystalline with well-aligned structure. These fibers have higher tensile strength than glass fibers or synthetic organic fibers, good elasticity, and excellent resilience [8]. The studies investigating the crashworthiness of composites with natural silk fibers as reinforcements were primarily the outcome of our investigation [9–14].

The current study investigated the energy absorption and load carrying capability of woven natural silk epoxy–triggered composite tubes under an axial quasi-static compression test. In this research, the failure of woven natural silk was investigated and the failure mode was described in detail. The effect of triggering mechanism on crashworthiness characteristics was investigated and compared to earlier work which investigated the same material under quasi-static compression but without trigger mechanism [14].

2. Materials and method

Woven natural silk/epoxy square tubes with 30 layers of woven natural silk fabric and an epoxy resin matrix (for more details please refer to [11,13]) with a total thickness of 4.2 mm were subjected to a quasi-static compression test by using a fully equipped and automated INSTRON MTS 810 universal testing machine with a 250 kN loading capacity. All tests were performed at a constant test crosshead speed of 20 mm/min. Two flat plates as fixtures and four-piece trigger (rectangular metal pieces) were used to accomplish the test. Each piece of the four-piece trigger was located over the

* Corresponding author. Tel.: +60 3 89216504.
E-mail addresses: sorena.a@eng.ukm.my, sorena.a2569@gmail.com (R.A. Eshkoor).

http://dx.doi.org/10.1016/j.compositesb.2015.03.017
1359-8368/

fixture plate. The pieces met at the center of the edge of one side of the tube. Fig. 1 shows the configuration of the four-piece metallic trigger.

Finally, the quasi-static test results of the tubes with 12 layers [11] and 24 layers [13] were added for comparison and extensively discussed.

3. Results and discussion

Figs. 2(a)–4(a) show the representative photographs of axial quasi static compressive tests of tubes with 30 layers woven natural silk. Figs. 2(b)–4(b) show the load–displacement curves attributed to each tube.

As shown in Figs. 2(a)–4(a), all woven natural silk/epoxy composite tubes with 30 layers failed in local buckling mode. Two main peak loads were observed in the load–displacement curves of the woven natural silk/epoxy composite tubes for the 30 layers [Figs. 2(b)–4(b)]. At the first peak, load failure at the intersections of the tube and triggers were initiated, followed by a sharp decrease in load. As the triggers fully indented the tubes, the bottom side of the tube contacted with the downside flat plate. The load increased again until it reached the second peak load. Local buckling failure mode was observed to have occurred. The required load was significantly decreased at the second peak load, with the formation of circumferential cracks of the tube.

3.1. Failure modes

Mamalis et al. [15] observed three modes of failure in brittle composite structures based on epoxy resin: progressive end-crushing, local buckling and mid-length buckling. However, two other failure modes were also considered in the Hull classification [16]: Euler overall column buckling and progressive folding with hinge formation.

The load carrying behavior of natural fibers must first be understood before they can be extensively used as reinforcement in energy absorbing systems [17]. In the present study, Euler overall buckling and progressive end-crushing failure were not observed in the woven natural silk/epoxy–triggered composite tubes. These tubes failed in a slightly different manner compared with brittle composite tubes due to the elastic properties of natural silk fibers which has been earlier reported in Ref. [8].

The failure mode of the woven natural silk epoxy–triggered composite tubes was a combination of some failure modes mentioned above. Generally, buckling and hinge formation were the two principal failure characteristics of woven natural silk epoxy–triggered composite tubes. Therefore, their failure was a combination of modes II and III of the Mamalis classification and

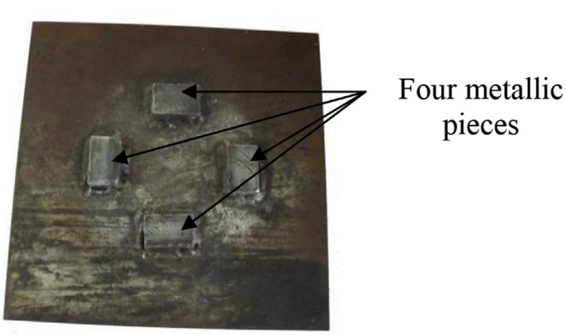

Fig. 1. Four-piece metallic trigger located on a flat plate.

hinge formation of the Hull classification. In contrast to brittle composite tubes, the woven natural silk/epoxy–triggered composite tubes showed no wedge debris formation, nor an inward and outward spread of fronds. The failure modes observed in this study were local buckling and mid-length buckling associated with hinge formation.

Mid-length buckling was only observed in the woven natural silk epoxy–triggered composite tube with 12 layers and 120 mm length. All other tubes failed in local buckling mode.

Both local buckling and mid-length buckling were observed in the tubes after the second peak load, which was the maximum recorded peak load during the axial quasi static compression test of each tube. Generally, the local buckling mode in tubes with no triggering mechanism may have initiated from the top side of the tube that contacts with the upper moving press crosshead or from the bottom side of the tube that contacted with the stationary one [15]. The failure of tubes accompanied by trigger mechanism initiated from the intersection point of the trigger and tubes, and then propagated along the tubes [18]. In the woven natural silk epoxy–triggered composite tubes with 50 and 80 mm lengths and with 12 layers, the failure initiated from the trigger point but the local buckling failure mode unexpectedly started from the top side instead of the bottom side where failure was initiated by the trigger. This result can be attributed to the geometric effect on the type of failure mode. The failure stages of tubes can be followed while simultaneously observing variations on the load–displacement curve by designating sequential numbers to representative photos and load–displacement curve in each figure.

The dominant failure mode was mid-length buckling. Only the woven natural silk/epoxy non-triggered composite tubes with 50 and 80 mm lengths and 12 layers failed in local buckling [14]. In the present study, the dominant failure mode was local buckling, and only the woven natural silk/epoxy composite tube with 120 mm length and 12 layers showed mid-length buckling. This remarkable difference in failure modes of specimen can be attributed to the effect of the triggering mechanism that was employed in this study.

The 12-layered woven natural silk/epoxy composite tubes with 50 mm length failed in local buckling, regardless of the employed trigger configuration. The local buckling in both specimens was initiated from the top side. In addition, the specimens with 80 mm length regardless of the employed trigger configurations failed in local buckling mode. The mid-length buckling failure mode in the woven natural silk/epoxy composite tubes with 120 mm also remained intact regardless of the employed trigger configuration. This phenomenon demonstrated that geometry was a predominant factor that affected the type of failure mode in quasi static compression test. This result agreed with those of previous work [15,17]. Other specimens with trigger failed in local buckling mode, whereas those without trigger failed in mid-length buckling. This phenomenon is attributed to the effect of trigger mechanism on failure mode.

The failure of structures has been divided into two categories: catastrophic and progressive failure [12]. They are distinguished by the load–displacement curve behavior and crush force efficiency of structure. Both criteria pertain to the proportion of sustained average load value to peak load value. However, progressive failure occurs when the sustained average load is close to peak load.

The comparison of load–displacement curve between non-triggered [14] and triggered specimens showed that the non-triggered specimens failed in a catastrophic manner. Meanwhile, the triggered specimens due to decline in peak load value failed in a progressive manner. Pitarresi et al. [18] mentioned that composite structures generally fail in catastrophic mode unless a trigger mechanism is employed.